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DESIGN OF A CONTROLLER FOR A FLEXIBLE POINTING SYSTEM USING H_∞ SYNTHESIS

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13. ABSTRACT (Maximum 200 words)

This report presents the results of a digital controller design implementation using the *H*-infinity synthesis method on the ATB 1000 test fixture at the Army Research Development Engineering Center (ARDEC), Picatinny Arsenal, NJ. The objective was to design a robust tracking controller to make the beam tip track a reference command applied to the base in the face of nominal disturbances. In this report, the salient features of the design approach will be reviewed and the implementation issues that arose will be discussed at length.

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FIGURES

FIGURES (cont)

INTRODUCTION

The problem statement as described in the introductory papers (refs 1 and 2) was to design a controller to make the beam tip track a reference command applied to the base in the face of nomina disturbances.

The ATB 1000 test fixture (fig. 1) was designed to study various advanced control methods. It is a scaled down version of an advanced weapons system mounted on combat helicopters and it emulates the two-dimensional gun motion. The barrel is a 1-m long thin flexible beam whose modes correspond to the flexible modes of the actual gun barrel. The beam is coupled to an inertia wheel which is rotated by the turret motor mounted at the top of the fixture. The voltage supplied to the turret motor serves as the control input.

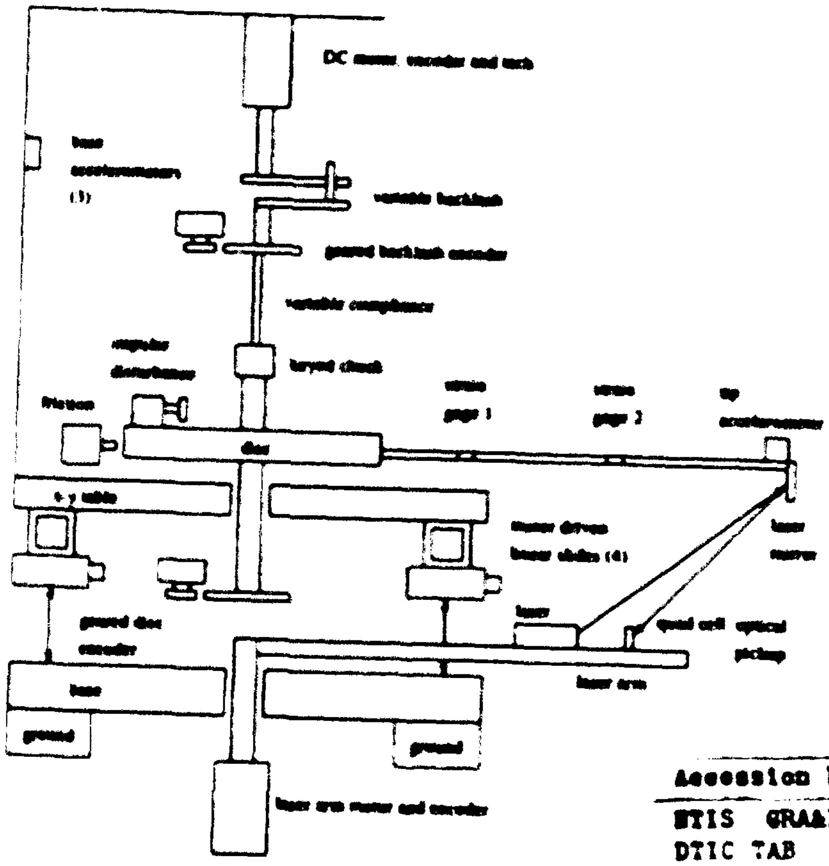

Figure 1. ATB 1000 test fixture

A solenoid is mounted on the inertia wheel to simulate the effect of firing disturbances in the system due to gun recoil which is modeled to be periodic and impulsive in nature. In addition, four motor slides are mounted at the base to simulate the effects of base disturbances, which are modeled to be sinusoidal in nature and provide lateral and axial motion. Also, an adjustable mechanism is provided on the shaft for varying the backlash.

There are various sensors mounted on the structure which provide the measured outputs for our feedback design. Namely, the motor and backlash encoder in counts, the inertia wheel encoder for the base position in counts, strain gauges located on the beam at one-fourth and one-half the beam length, a motor tachometer, and a tip accelerometer. Two sensors, the quadcell position (tip position) and the quadcell sum, were provided but unavailable for feedback.

The fixture allows varying levels of different nonlinearities such as friction, stiction, and backlash to be introduced into the system. This recreates the behavior of the actual gun and also provides insight on the operation of other rigid body dynamical systems.

A nonlinear model of the fixture implemented using SystemBuild on MATRIX$_X$ is shown in figure 2. The barrel was modeled as a linear system with two rigid body modes and three flexible body modes. This model was obtained from a finite element analysis of the beam. The flexible modes of the beam are at 30.2, 138, and 385 rad/s (4.8, 22, and 61 Hz, respectively). The motor, which drives the inertia wheel, was essentially modeled as two integrators. From figure 2 it can be seen that there are feedback loops with the dynamics of the turret system. Hence, it turns out that the often loop system has four lightly damped modes at approximately 27.5, 53, 138, and 385 rad/s. This can be seen in figure 3, which is a plot of the open loop frequency response of the system from the motor input to the tip position.

DESIGN SPECIFICATIONS

The primary objective of the design problem was to make the tip of the beam (of the test fixture) track a reference command in the face of nominal disturbances. The reference commands for the beam tip position consisted of the following:

- Steps, from 0 to a maximum of 1.396 rad, the maximum range of motion is $\pm$1.396 rad

- Ramps (or a series of ramps) with slopes no greater than 1.396 rad/s.

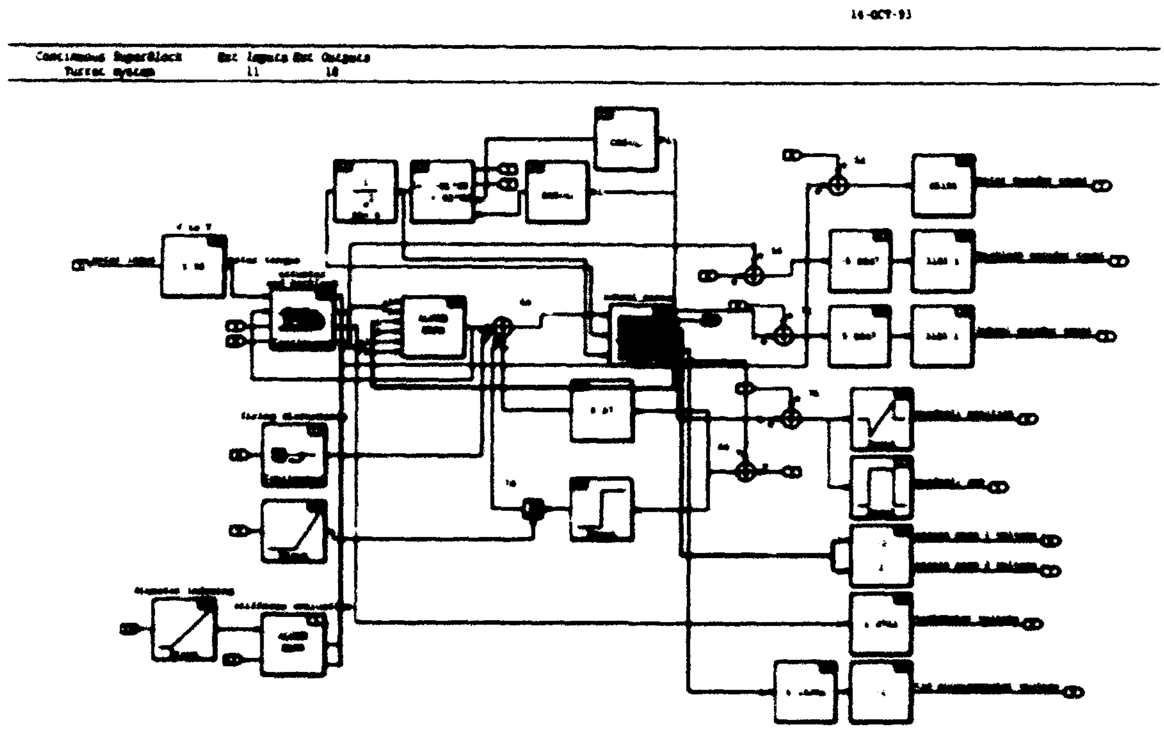

Figure 2. Nonlinear model of turret system using SystemBuild on MATRIX$_X$

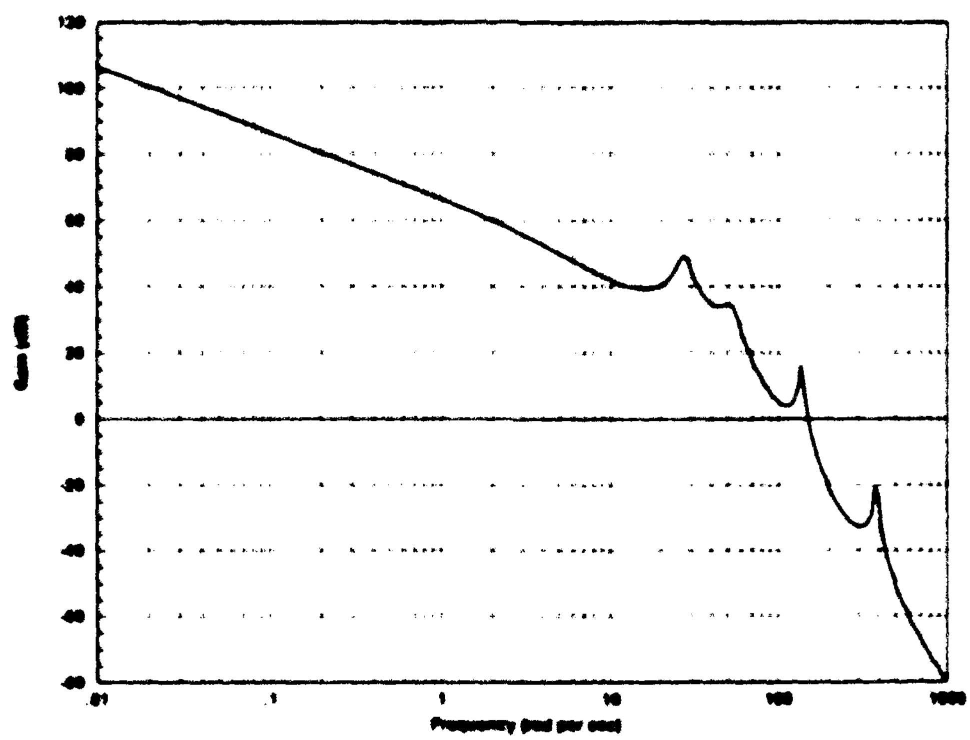

Figure 3. Open loop frequency response from motor input to tip position

The external disturbances were of two types:

- Base disturbance, which is sinusoidal in nature with amplitudes from 0.5 to 1.0 V and frequencies in the ranges of 3.5 to 4.5 Hz and/or 21 to 23 Hz.

- Firing disturbance, which is impulsive in nature and periodic in the ranges of 3.5 to 4.5 Hz and/or 21 to 23 Hz.

To achieve good tracking performance, these disturbances had to be attenuated at the tip. Some additional complexity was added to the design problem due to the following observations:

- The frequencies of the disturbances are very close to frequencies of the flexible modes

- Although the tip should track step and ramp inputs, the tip position is not measurable and hence is not available for feedback control

- The beam is a flexible structure as opposed to a rigid body

- The transfer function from the motor input to the tip position is non-minimum phase

There is a nominal disturbance frequency of 25 rad/s (approximately 4 Hz) (fig. 3) which is very close to the first two flexible modes. The controller needs to have a loop gain large enough to control the flexible modes of the beam in the frequency range of the disturbances and then roll off fast enough so as not to excite the higher flexible modes. The controller design was based on the nominal model of the plant and disturbances.

As a design objective, we wanted the controlled to be robust to $\pm$ 10% variations in the flexible modes of the plant and the disturbance frequencies. Noise had to be accounted for in the measurements used in the design and the computational delay involved during the implementation.

The turret system is a fairly complicated nonlinear plant. A linear controller was first designed for the linearized plant at the nominal operating conditions. This controller design was later modified using the *D*-implementation (refs 3 and 4) to account for the nonlinearities in the system. Thus, the final controller provides tracking, firing disturbance attenuation, and is robust to uncertainties in the flexible modes.

The H_∞ optimal controller synthesis procedure (ref 5) was used to design a digital controller for the turret fixture.

SYNTHESIS MODEL

Consider the feedback system in figure 4. Here G is the generalized model (plant with design weights of the text fixture and K is the continuous time controller.

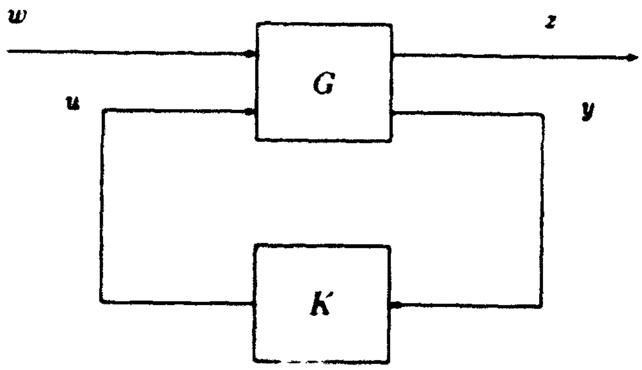

Figure 4. Feedback interconnection of G and K

Let T_{zw} denote the closed loop operator from the exogenous inputs w to the performance variables z. The objective was to keep the effect of w on z small. The H_∞ synthesis procedure solves the problem of finding among all controllers that yield a stable closed loop system, a controller K such that the H_∞ norm of T_{zw} is minimized.

This idea was used to construct the feedback system in figure 5, where the blocks and signals within the dotted lines constitute the synthesis model G. The block P is the linear model of the turret system and K_d is the digital controller to be designed. S_T and H_T represent the appropriate sample and hold operators associated with the discretization of the continuous time controller K. A digital high pass filter was incorporated in the feedback path to eliminate effect of noise in the sensor measurements. In addition, a transfer function of the form

$$\frac{1 + sT}{1 - sT}$$

where sampling period T << 1 s was incorporated to account for the computational delay.

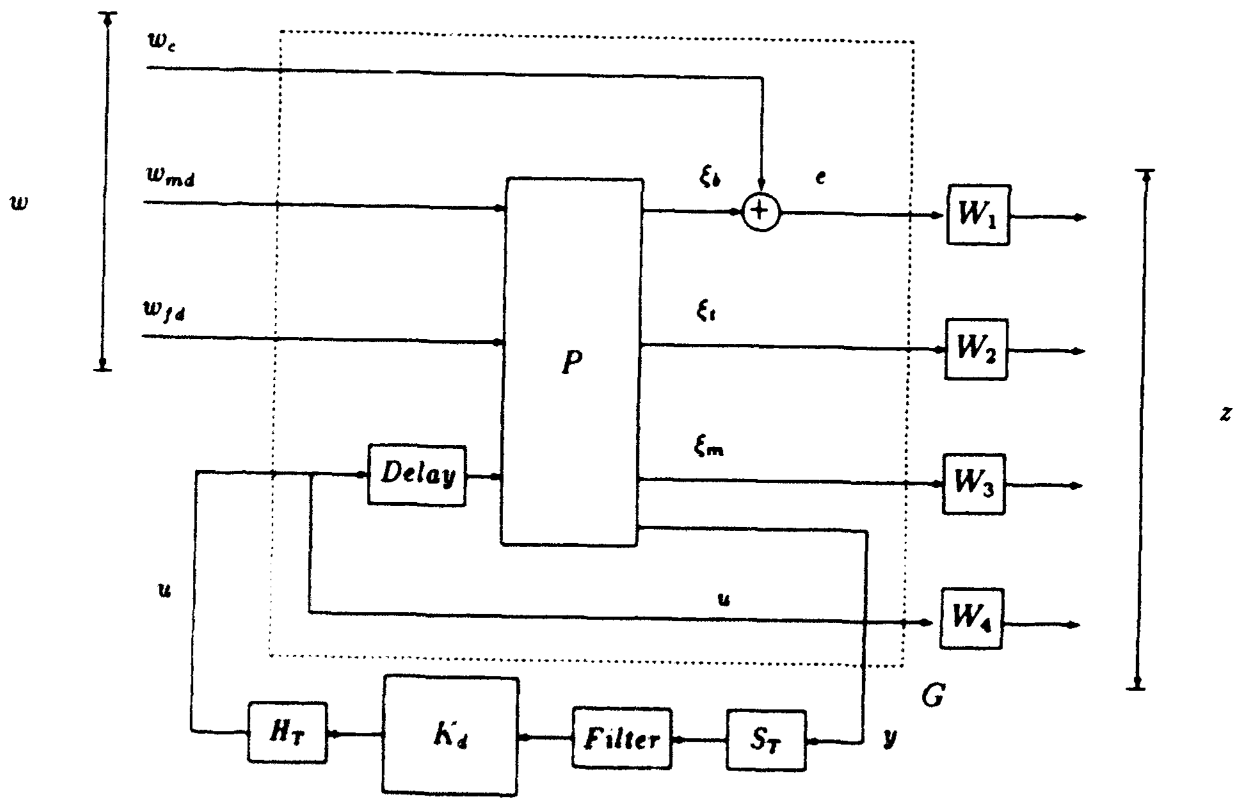

Figure 5. Synthesis model

The selection of w and z in figure 5 was based on the following performance requirements:

- The command loop bandwidth should be about 5 rad/s. This means that the time constant in the step response of the tip position is about 0.2 sec, which is sufficiently fast to satisfy the reference command tracking requirements.

- The disturbance rejection at the tip should be 95% or better for both disturbance inputs.

- Loop crossover frequency should not exceed 250 rad/s, which implies the first three lightly damped modes of the turret system are controlled.

- The closed loop damping ratios of the rigid body modes should be at least 0.7 and that of the flexible modes should be at least 0.2

The exogenous input vector w includes:

- w_c - command signal (step/ramp) to be tracked
- w_{md} - motor input disturbance
- w_{fd} - firing disturbance

The signal u represents the control input to the system, which was the voltage applied to the turret motor. The signal y denotes the measured output of the plant. This included all the outputs of the turret system that were measured by sensors. Since the tip position is not measurable it is not included in y, although the goal was to track signals at the tip. This tracking objective was accomplished by actually tracking signals at the base (inertia wheel).

The output $\xi := (\xi_b' \xi_t' \xi_m')'$ of the block P represent the performance (regulated) variables. These signals need not be real outputs of the turret system, but can be fictitious output signals that are weighted to obtain the synthesis model. In this case, the signal ξ consisted of:

- ξ_b - inertia wheel position (rad), for generating the tracking error
- ξ_t - tip position (rad), for disturbance attenuation
- ξ_m - the states of the first three bending modes to achieve closed loop damping requirements for the bending modes.

In the model of the turret system, the quadcell position and the iwheel encoder signals were divided by the respective sensor gains to convert the units from counts to radians corresponding to the actual signals. The blocks W_i represent the weighing functions that were chosen to reflect the design objectives. Since the base (and the tip) have to track step inputs, an integrator was put on the tracking error e. So $W_1(s) = c_1/s$, where the constant c_1/s, where the constant c_1 was during the design procedure to achieve the desired tracking properties. The weight on the integrator c_1 will determine the command bandwidth, (i.e., the bandwidth of the transfer function from the reference command to the tip position). To provide zero steady state error value and rejection of constant disturbances at the base (and the tip), the output of W_1 was included in z. Also, since the disturbances (at 25 rad/s) have to be attenuated at the tip, a stable dynamic weight of the form

$$W_2(s) = \frac{s + 0.1}{s^2 + s + 625}$$

was used on the tip. W_2 has a pair of lightly damped complex poles with natural frequency of 25 rad/s and contains a large gain at the disturbance frequency of 25 rad/s. Such a frequency dependent weight would desensitize the tip of the beam to the input and firing disturbances. The weight W_3 is a gain on the states of the bending modes which was adjusted during the design procedure to achieve the desired closed loop damping on the bending modes. Finally, since unreasonably large control inputs were not wanted, (a weighted) motor input signal was included as one of the regulated variables. So W_4 is a weight, which will determine the control bandwidth. The control bandwidth usually corresponds to the crossover frequency of the loop gain. The outputs of the blocks W_1, W_2, W_3, *and* W_4 were included in the regulated variable z. The weighing functions W_i were adjusted based on the input-output command response, loop gain actuator bandwidth, and the disturbance rejection requirements.

The synthesis model constructed for the design is shown in figure 6.

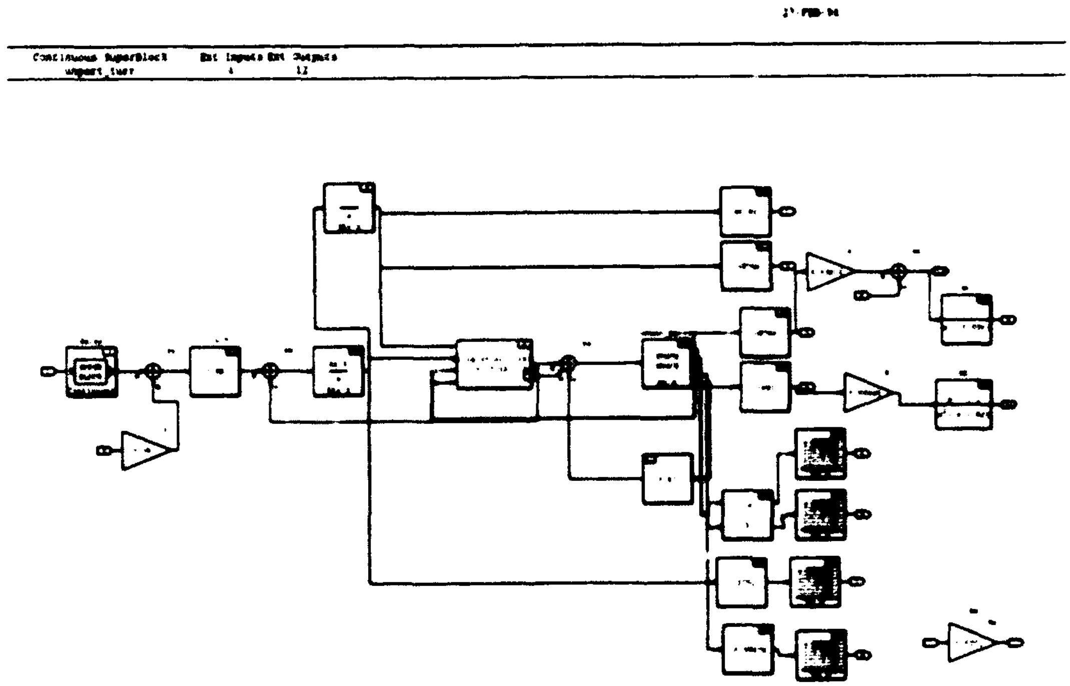

Figure 6. Constructed synthesis model

A continuous-time state-feedback controller was first designed using the synthesis model developed in figure 6. This design gives an idea of the maximum performance limits which could have been achieved had all the continuous-time measurements been available for feedback. Using the design weights from the continuous-time design, an output-feedback controller was designed and iterations performed on the weights to preserve the performance levels. This design was then discretized at a suitable sampling rate to obtain the desired digital controller.

CONTINUOUS-TIME CONTROLLER DESIGN

As mentioned in the previous section, a state-feedback controller was first designed assuming all the states were available and then designed an output-feedback controller iterating upon the weights to achieve the desired performance. The comparison of the loop gains for the two designs is shown in figure 7.

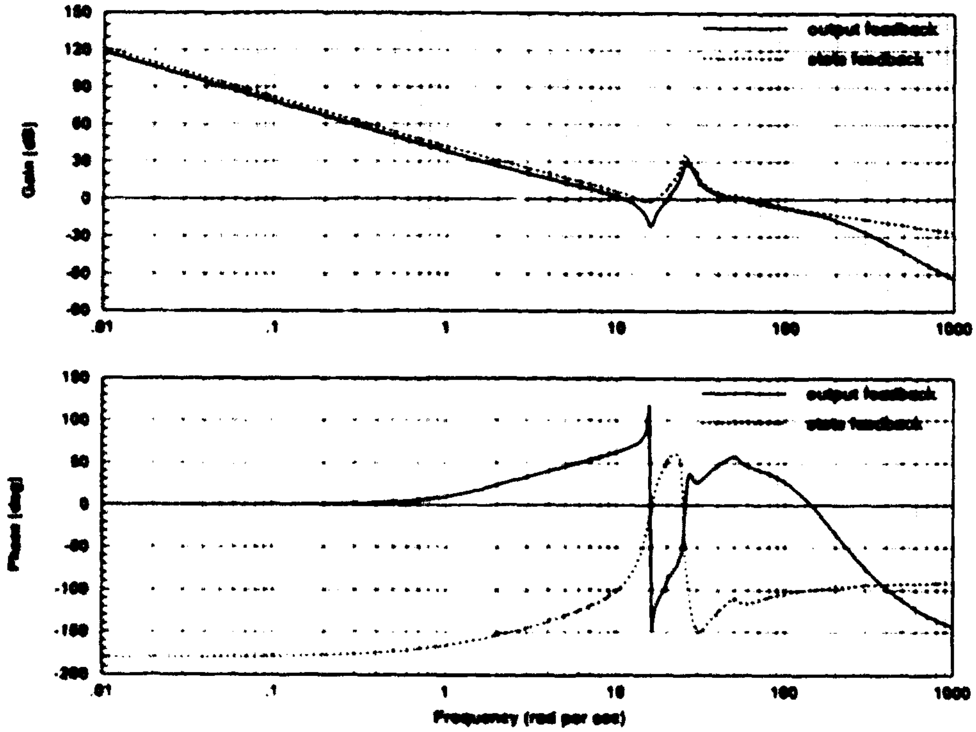

Figure 7. Loop gains for state and output feedback controller designs

As seen in the plots, the output-feedback design emulates the state-feedback design over the frequency range of interest (*viz.* 0 to 138 Hz). The designs have the loop gain peaking at the first flexible mode frequency which is very near the disturbance frequency of 4 Hz (25 rad/s).

The performance levels achieved are shown in the sensitivity plots of figure 8. The attenuation at the tip to the firing disturbance is -15 dB, while that to the motor disturbance is -30 dB. The command bandwidth is 2 rad/s.

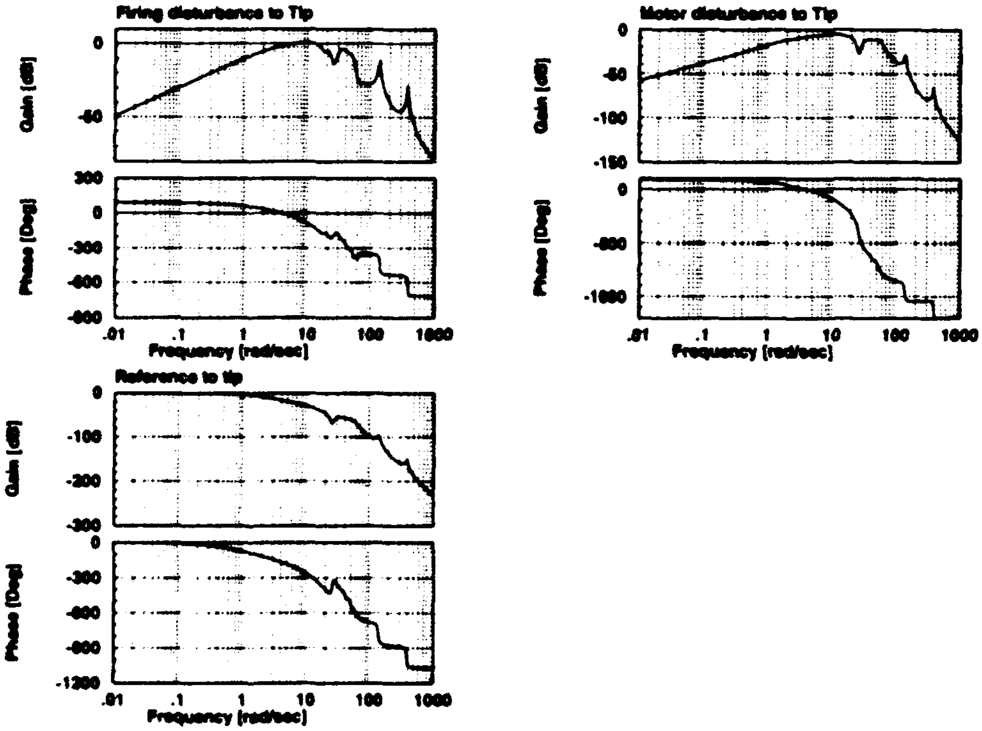

Figure 8. Performance plots for disturbance rejection and command bandwidth

It was wanted that the designed controller to be robust to ±10% variations in the frequency of the flexible modes. The plots for the reference command tracking with variation in the flexible mode frequencies are shown in figure 9. The three parameters plotted are:

- The reference command consisting of a combination of ramps having a maximum slope of 1.4 rad/s, which is the upper limit on the allowable values

- The iwheel position which, in place of the tip position, should track the reference command

- The control input generated by the controller

From the plots, it can be seen that the design is stable to variations in both the positive and negative directions. It should be noted here that the preliminary design results had better tracking performance in the computer simulations than the results featured below, but were found to give rise to instability when implemented on the test fixture. The results shown here are the final design results obtained after the digital controller performed satisfactorily on the test fixture. This issue will be discussed at length in the ensuing sections.

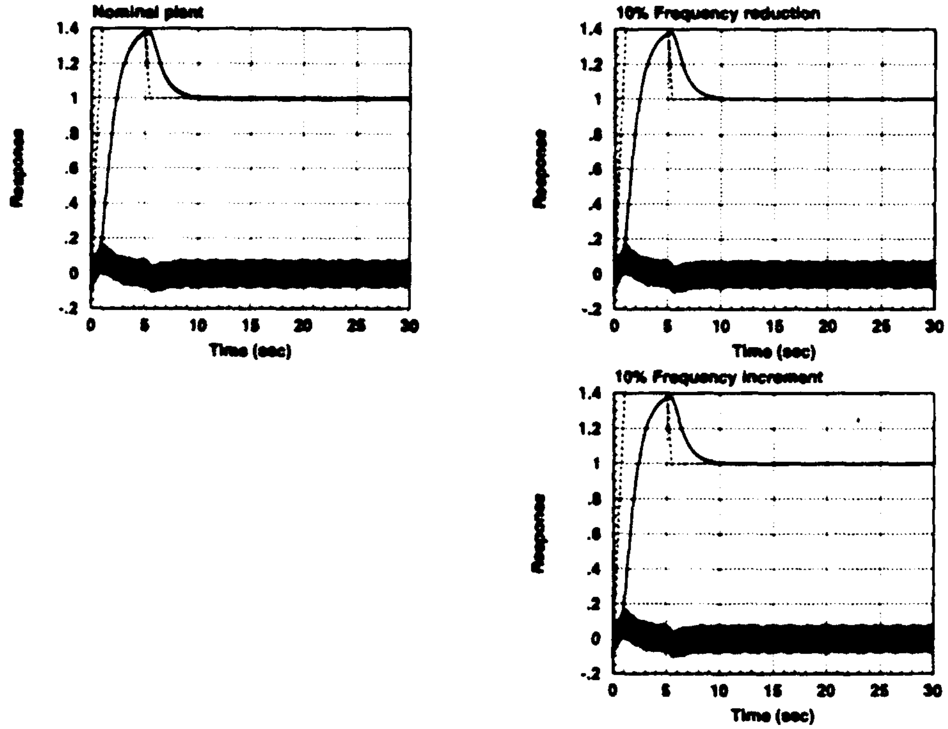

Figure 9. Reference command tracking and control input with variation in the flexible mode frequencies

DIGITAL CONTROLLER DESIGN AND IMPLEMENTATION

Having developed a continuous-time controller which satisfied the performance requirements, the design was then discretized using a sampling rate of 400 Hz. This rate was found to be fast enough to preserve the performance levels, and at the same time could be implemented on the fixture hardware. The delay was chosen to be one sampling period corresponding to the 400 Hz sampling rate.

For the sensor noise rejection, high pass filters were appended in the synthesis model on the appropriate measurements and in our nonlinear simulations. However, due to the warping effect in their digital versions, the high pass filters were converted to band pass with roll off at 60 Hz. This was achieved using 8th order Chebychev type II filters.

To preserve the internal and input-output properties of the linear closed-loop system, locally about the equilibrium point in the nonlinear system, the *D*-implementation method was used. This is achieved by differentiating some of the measured outputs before they are fed to the controller and providing integral action at the input to the plant. Difficulty of incorporating pure differentiators was circumvented by placing them with delays. A detailed treatment of the *D*-implementation is given in reference 3. The real time D-implementation controllers are shown in figure 10 and 11.

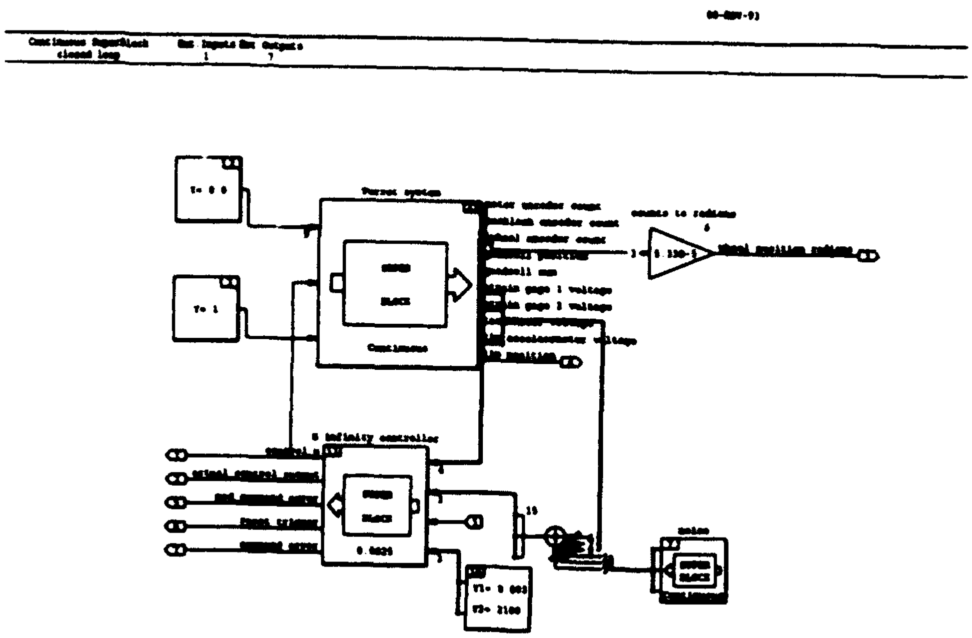

Figure 10. Closed loop sampled-data system with simulated noise and disturbance

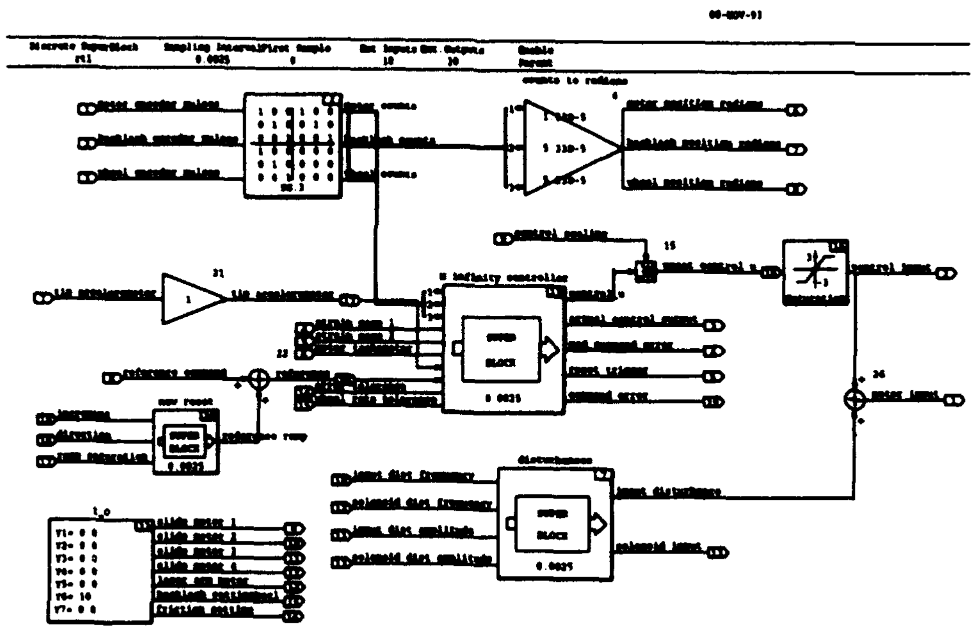

Figure 11. H_∞ controller scheme for real-time implementation

Prior to incorporating the D-implementation it was observed that when small step commands were applied to the base, the controller would do the following:

1. It would continue to integrate on the command error even after the reference command was turned off, causing the motor input to increase when it should have been zero.

2. The oscillations in the motor input and tracking response would change frequency early on. This indicated that the controller was somehow exciting the plant modes.

3. When the turret motor was switched off the controller would go into saturation.

A first approach was to increase the gain on the first bending mode, which had the effect of lowering the frequency and amplitude of the oscillations but did not solve problems 1 and 3.

A logical reset was also incorporated in the controller scheme to set the value of the command error to zero if it fell below a value of ±2100 counts/s. The D-implementation design with an anti-windup scheme and reset (fig. 12) solved these problems. Stable tracking was achieved by lowering the DC loop gain to the value shown in figure 7. The plots for the reference command tracking with variation in the flexible mode frequencies now resemble those shown in figure 9.

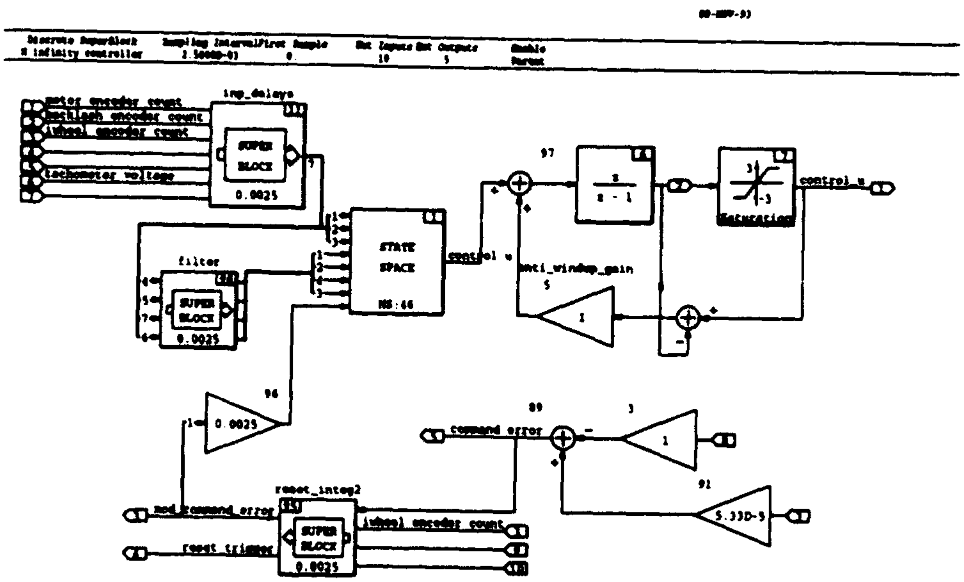

Figure 12. H_∞ controller with D-implementation, anti-windup scheme and reset

The controller has good tracking response as seen in both the simulations of figure 13 and on the actual test fixture results of figure 14. It can be seen that the controller tracks steps and ramps in both directions in the absence of the firing disturbance. However, it was noticed that in the closed loop frequency plot from the firing disturbance to the tip position, the controller was unable to provide sufficient attenuation of the 4 Hz mode. The excitation at this frequency caused the tip to oscillate while tracking ramps or steps.

The next step was to achieve sufficient disturbance rejection at the 4 Hz frequency. One approach was to apply a gain on the disturbance input that the controller will see in its synthesis program. This is a valid approach since no changes were made in the plant setup and it will result in a lowering of the sensitivity, while to a large extend preserving the desired performance characteristics. However, there is a limitation on the achievable attenuation by this approach before it results in performance degradation. A 15 dB attenuation was achieved by this approach.

Another approach would be to apply the filter currently located on the tip at the input to the disturbance itself, to eliminate the effect of the 4 Hz mode. This would involve altering the synthesis model and hence the choice of weights to reflect the desired performance requirements. The current work is on this approach.

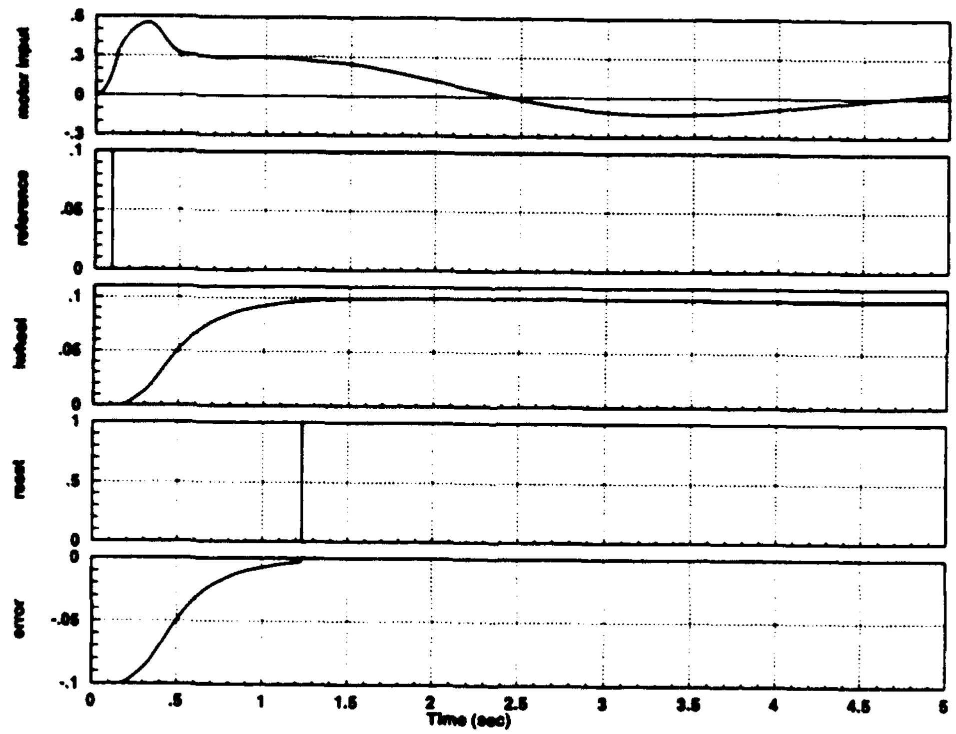

Figure 13. Simulation result of the digital controller on the nonlinear plant to a reference step command of 0.1

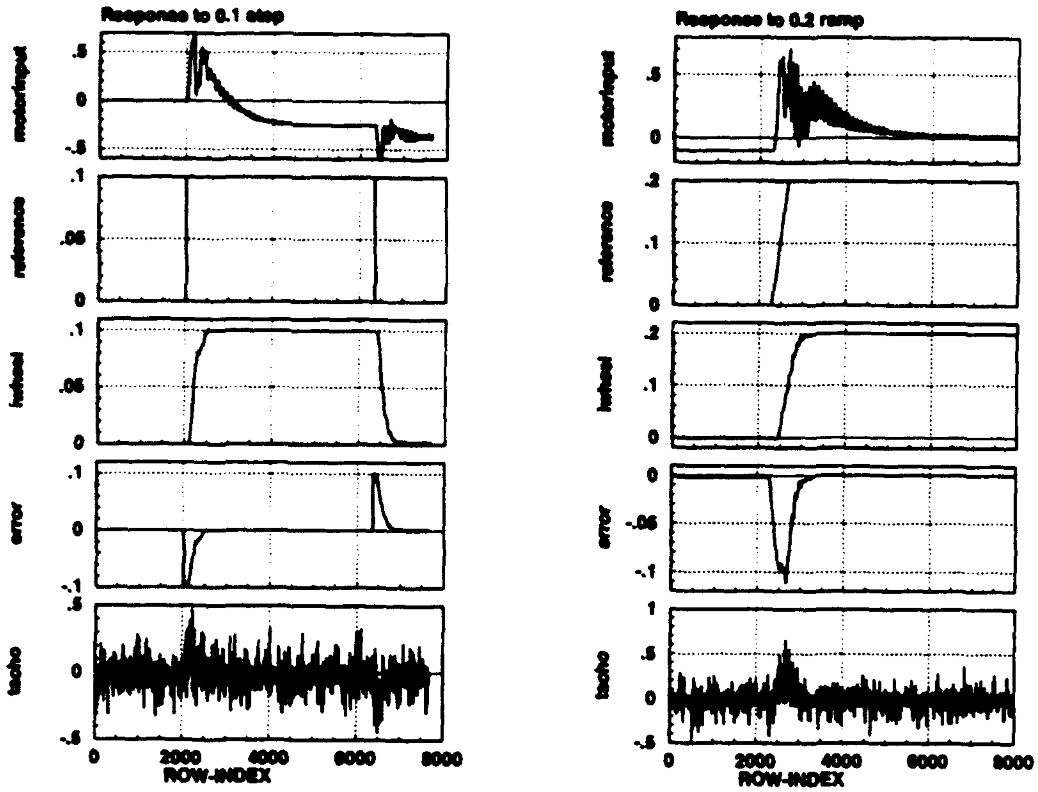

Figure 14. Actual result of the digital controller on the test fixture (Row-index = time x sampling rate of 400 Hz)

CONCLUSIONS

From the test results, it was observed that the controller designed by this methodology has good tracking performance for both step and ramp commands applied to the base (inertia wheel). It is also robust variations of ±10% in the frequency of the flexible modes. This methodology also leads to a greater degree of freedom in the choice of weights for achieving the desired performance requirements.

REFERENCES

1. Mattice, M. A Nonlinear Flexible Pointing System for Digital Control Research, Proc. AAC, WM 13, pp 526-30, 1993.

2. Sivashankar, N.; Kaminer, I.; Khargonekar, P.P., Design of a Controller for the Turret System Using H_∞ Synthesis, Proc. AAC, TM 13, pp 1612-16, 1993.

3. Kaminer, I.; Pascoal, A.M.; Silvestre, C.; and Khargonekar, P.P., Control of an Underwater Vehicle using H-infinity Synthesis, Proc. 30th IEEE Conference on Decision and Control, pp 2350-2355, December 1991.

4. Kaminer, I., Application of H-infinity Synthesis to the Motion Control of Rigid Bodies and Related Theory, Ph.D Dissertation, University of Michigan, July 1992.

5. Sivashankar, N., Robust Sampled-Data Systems, Ph.D. Dissertation, University of Michigan, December 1993.

BIBLIOGRAPHY

1. Kaminer, I. and Kharonekar, P.P., Design of the Flare Control Law for Longitudinal Autopilot Using H-infinity Synthesis, Proc. 29th IEEE,Conference on Decision and Control, pp 2981-2986, 1990.

2. Kaminer, I.; Khargonekar, P.P.; and Robel, G., Design of a Localizer Capture and Track Controller for a Lateral Autopilot using H-infinity Synthesis, Control Systems Magazine, Vol 10, No. 4, pp 12-21, 1990.

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